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"Sediment Delivery Below Roads in the Oregon Coast Range"
THE UNIVERSITY OF IDAHO
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COOP Agreement
Univ of IDAHO



# Sediment Delivery Below Roads in the Oregon Coast Range

Final Report

from

The Biological and Agricultural Engineering Department
University of Idaho

to

Rocky Mountain Research Station
Forest Service, USDA

Agreement No. INT-95081-RJVA

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College of Agriculture
UNIVERSITY OF IDAHO
College of Engineering

# Sediment Delivery below Roads in the Oregon Coast Range

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## Abstract

Forest roads have been shown to be a major contributor of sediment to streams. Steep slopes associated with forest road cuts and fills are often a long-term source of sediment. Traffic on the road and maintenance grading continuously rejuvenate the supply of fine sediments. In areas of designed concentrated runoff such as ditches and cross-drains, flow can continually erode the surface and carry the fine sediments further downhill. Thus, forest roads are a potential long-term source of soil particles, transported material downhill, and stream sediments. In order to further understand forest road erosion and mitigate the problem of increased stream sediments, managers need to know how much sediment is being generated from existing roads and how far that sediment moves below the roads.

A site-specific empirical model relating topography, soil texture, and vegetation indices and transported sediment plume lengths found below culverts was developed. Variables were measured at 120 sites within forested watersheds of the Oregon Coast Mountain Range. Total sediment travel distances were determined by the length of a sediment plume found below culvert openings and did not try to account for suspended sediments not deposited along the immediate hillside. An empirical model was developed to help land managers better understand the importance of road design features, such as road slope, culvert spacings, and cutslope management on sediment delivery through designed concentrated flow via ditches and cross-drains.

## INTRODUCTION

It is estimated that 50 to 90 percent of excess sediment from forest activities originates on the road systems (Elliot *et al.*, 1994). The largest sediment loss occurs in the first two or three years following road construction. Sediment loss has been shown to decrease substantially after the initial disturbance as cut- and fillslopes stabilize and become revegetated within a few years (Burroughs and King, 1989; Ketcheson and Megahan, 1996). During road construction, topsoil is lifted and displaced which destroys the filtering potential of the duff and organic soil layers. Further compaction during and after construction destroys the surface water absorption potential. After the initial construction period, most of the eroded sediment comes from the travelway within the road prism due to the lack of vegetation on the travel surface, traffic, and maintenance grading. The exposed soil on the travelway is susceptible to rain-drop splash erosion, sheet erosion, and rilling. Thus, forest roads can potentially serve as sources for erosion processes as runoff travels over the road surface prism. Over time, sediment production tends to decrease due to the armoring of the soil surface and increases in established vegetation.

Common road design practices concentrate and manage runoff by the addition of an interceptor ditch on the inside of the road and insloped road surfaces to direct water into the ditches. The flow is directed across the road surface at pre-determined intervals in bedded culverts or cross-drains and flows further downhill toward receiving streams. Studies have shown (Haupt *et al.* 1963) that the practice of insloped roads decreases sediment delivery compared to outsloped roads which allows runoff to traverse newly constructed and unstable fillslopes before reaching a natural forest floor and the original hydraulic gradeline. However, while use of inside ditches and cross-drains may protect fillslopes, the more concentrated flow at culvert outflows has increased erosion potential. To ensure dampening of the energy developed in concentrated flow, proper culvert spacing is critical. Managers need to know site-specific factors influencing culvert spacings, prediction equations need to be developed with locally significant input parameters in the erosion model.

There have been relatively few empirical studies on sediment delivery below forest roads in the western forests of the United States. In the snow dominated climatic zone of the northern Rocky Mountains, some studies have related sediment flow distances to road and site characteristics. Haupt (1959) measured flow distances below 75 surface cross drains on a granitic road that just had been closed to the public. He developed a regression equation to predict sediment flow distance. In order of importance of explaining sediment flow distance, the variables used in his regression were an index of slope obstruction density, contributing road length squared, fillslope length, and the product of contributing road length and slope.

Ketcheson and Megahan (1996) measured sediment flow lengths below new landings, fillslopes, and three types of road drainage features on midslope forest roads constructed on granitic soils in Idaho. They developed a regression to predict the logarithm of sediment travel distance below culverts. Significant independent variables were the logarithms of hillslope gradient, source area, obstructions, and sediment volume.

Packer (1967) measured sediment flow distances below a total of 720 road segments representing six different geologies in the Northern Region of the Forest Service. This study looked at sediment travel distances below surface cross drains on forest roads with no inside ditch or relief culverts. A regression used to predict sediment travel distance used average obstruction spacing and distance from road shoulder to first obstruction, type of obstruction, vegetated ground cover at culvert opening, and contributing road length.

Carlton *et al*. (1982) measured travel distances below fillslope rills and gullies for 25 road segments representing three different geologic types in northern Idaho. These flow paths were not associated with culverts, but entirely with rill and gully development on fillslopes. Travel distance of the sediment flows was significantly and positively correlated with the volume of the rill or gully; and significantly and inversely correlated with an index of obstructions to flow. Concentrated flow generated from the road tread influenced both the volume of the gully formed

in the fillslope and the sediment travel distance.

Campbell and Stednick (1983) investigated sediment movement below forest roads in a Colorado spruce-fir forest. These roads were drained using outsloped dips to divert water over the fillslope rather than concentrated drainage at one point via insloped ditches. In this study, simulated rainfall events were used to generate sediment flows rather than evaluating sediment flows following natural rainfall events. They developed a regression equation to predict sediment flow distance based on a road slope-length factor, the gradient of the general downslope, and percent canopy cover over the fill.

Burroughs and King (1989) report on travel distances of sediment flows below 2.5 km of new road constructed on gneiss and schist geology in central Idaho. They report mean travel distance of 22.2 m below relief culverts and 7.9 m below gullies formed on fillslopes. They also reported that drainage from the road surface which is diverted to the fillslopes, rather than through inside ditches to cross drain culverts, more than doubled sediment flow distances.

This study was implemented to better understand processes associated with sediment delivery and the relationship between road characteristics and sediment transport distances below culverts on the steep slopes associated with the mountains of the Oregon Coast Range. Measured variables included site-specific logging road and hillside topography, soil texture, and vegetation indices at 120 cross-drains on various hillslopes. The specific objective was to develop a relationship for sediment plume length on steep terrain below culverts.

## METHODS

### Site Selection

The study sites were selected were based upon replications of different aspects, soil textures, length-slope coefficients, and downhill gradients on the sandstone lithologies of the Oregon Coastal Mountains. All sites chosen for this study were within the boundaries of the BLM Coast

Range Resource Area (CRRA) and Lane County, Oregon. The average elevation of the watershed is 366 m with an annual precipitation of approximately 1630 mm per year. The ecosystem is dominated by commercialized Douglas-fir (*Pseudotsuga menziesii*) and associated vegetation types. Timber harvest for Lane County in 1990 was recorded as 800 million board feet of removal, the highest volume recorded in the Pacific Northwest.

Ninety-six study sites were originally selected for this experiment based upon four replications each of three aspects (North, South, and East-West), two soil textures (both coarse and fine sedimentary soil groups), two Universal Soil Loss Equation length-slope coefficients (low and high), and two hillslope gradients (low and high). Factors further refining sample populations from which sites were selected included: established roads (over five or more years since construction), presence of designed drainage system (ditches and relief culverts or daylight drainages with insloped road prisms), travelway widths typically between 3.5 and 4 meters (accommodating both recreational vehicles and logging traffic), graveled surface treatment (standard basalt aggregate, $D_{50}$ 3-in largest axis, with 4-in lift), with moderate traffic. These 96 sites were selected and measured over the 1994 and 1995 field seasons. The experiment was expanded in the 1995 and 1996 field seasons to include 24 additional sites on newly constructed roads (less than 5 years since disturbance) in the same region. All study sites were selected from existing culverts over various soil types, aspects, elevations, lengths, slopes, and road gradients.

Property ownership in the CRRA varies between public (BLM, Forest Service) and private landholders, and is generally checkerboarded by sector in complete one-section blocks. The watershed is very deeply dissected by the streams that drain it. Prairie Mountain, near the northern boundary of the Resource Area, has an elevation of 1,130 m. Triangle Lake is in a valley formed by several streams that have their confluence with Lake Creek and is at an elevation of about 210 m; the surrounding mountains have steep slopes and rise to elevations of nearly 600 m within one mile. The major drainages include Long Tom River, which drains into the Willamette River, and the Siuslaw River and its tributaries. The soils along the Long Tom River are moderately well-drained to very poorly drained; the soils along Lake Creek are well

drained and moderately well drained.

This specific study area was chosen based upon specific soil types common to the region, intense cable yarding operations during timber harvest on steep slopes, availability of public lands, and the presence of suspended sediments in the watershed outflow.

The dominate soils of interest in the CRRA were chosen for their erosion potential and sediment production: the Bohannon series (fine loam, mixed, mesic, Andic Haplumbrept) and Honeygrove series (clayey, mixed, mesic, Typic Palehumult). The Honeygrove soil group is moderately deep to deep (greater than 0.1 m), well drained, gently sloping to very steep, silty clay loam formed in material weathered from sandstone or mixed sedimentary-igneous rock and commonly a dark reddish-brown; subsurface soils were often red. In a very generalized sense, these fine textured soils were more commonly located on the eastern half of the CRRA. The Bohannon soil group is also moderately deep to deep, well drained, nearly level to very steep, gravelly loam that formed in material weathered from interbedded sandstone and siltstone and ranged from dark brown to dark gray in color, with yellowish-brown substratum. These more coarse soils were more commonly located on the western half of the CRRA. Disturbance to either soil group results in an easily distinguishable sediment plume. For the Honeygrove group, newly transported sediment plumes appear as red soil on top of a deeper organic surrounding layer; the Bohannon group provides a yellow plume over a darker brown soil. Exposed cutslope material is also a visibly different color than the undisturbed neighboring forest floor both above and below the road prism.

**Measurements**

At each cross-drain, the total road length contributing to that drain was initially determined. The contributing length was considered the length from the culvert at the bottom of the road drainage section to an uphill and adjacent culvert, or to an uphill crest in the road which divided and directed the flow. The total contributing length was measured and divided into five segments of

equal length (20 percent of the total road length) for a total of six cross-sections to best define the topography at each site (Figure 1).

The road prism was described using several observations and measurements taken at each of the six cross-sections. The values measured at each cross-section were averaged over the six cross-sections to obtain the site-specific data used in the analyses. Variables measured at each cross-section included:

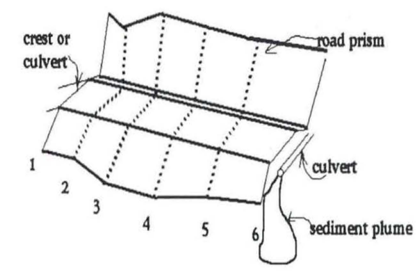


**Figure 1** Representative road prism showing 6 cross-sections dividing the roadway into 5 equal segments.

road:
- length
- width
- slope
- aspect
- contributing width of insloped surface
- surface width of the travelway

cutslope:
- length
- slope
- vegetative cover

fillslope:
- length
- slope
- width contributing to plume

ditch:
- depth
- top width

At the culvert outfall, the following parameters were measured:

sediment plume:

length

aspect

gradient by section

downhill forest floor:

slope

vegetative cover

aspect

obstructions with a diameter greater than 2.5 cm:

type

number

distance

Basal area

tree range

tree density

elevation of the road at the culvert

The sediment plumes measured for this study were delineated solely by visible color or texture differences of the plume from its surroundings. Margins were distinguished by digging a small core and observing layered differences in soil type and signs of organic matter within the sediment record. Lengths of meandering and braided sediment depositions were measured along the longest centerline as well as perpendicular distances to the roadway edge. At the toe of most sediment plumes, a silt fence was constructed in order to determine if the visual toe was, in fact, the furthest point of sediment delivery. Future accumulation of sediment within the silt fence will indicate if the initial length measurement was conservative.

Soil samples were collected at each site for particle size analysis to compare geologies. One-kilogram sized samples were taken 1-meter away from the culvert opening within the boundaries of the sediment plume. Additional samples were taken from the travel surface, the cutslope, and

the ditch.

All data were for site-measureable variables. No attempt was made to determine the precipitation or runoff amounts since road construction. A separate Forest Service study is in progress to determine actual erosion, runoff and deposition rates.

## RESULTS AND DISCUSSION

### Results

Table 1 shows the range of plume lengths measured for all 120 sites. The maximum travel distance measured was 40.5 m on a new site with coarse lithology (Bohannon soil type). The maximum travel distance on an old site was 23.2 m, also on coarse soil. The mean travel distance on new roads was 9.33 m, and 5.09 m on old roads.

For the old roads, there were 24 combinations of soil texture, road USLE LS factor, downhill gradient, and aspect each with four replications for a total of 96 sites. For the new roads, there were a total of 24 sites at which measurements were taken. Tables 2, 3, 4 and 5 show the statistics of plume length for the downhill slope, road USLE LS factor, soil texture and hillslope aspect.

Generally, those sites with southern aspects, high downhill gradient, coarse textured soil, and high LS factors had the longest mean sediment plume.

Correlation and regression analyses were used to evaluate factors influencing total sediment travel distance of the 120 observed sites measured for this study. In addition to the measured variables mentioned previously, the following additional variables were included:

USLE length-slope coefficient
flowpath length across the road prism
effective width associated with the flowpath length

contributing surface area of exposed soil on the cutslope

Most of the variables used in the correlation analyses did not have a statistically significant ($P > 0.05$) correlation with plume length. The variables that did prove to be significant for old and new roads are shown in Tables 6 and 7. From this it can be seen that only for the new roads is the distance between culverts (road length) significantly correlated with the plume length. ~~only for the new roads~~. This indicates that once the initial surge of transportable sediment available from construction and the vegetation cover is available to shelter the raw slopes, little sediment moves downhill. This is also found in many other studies of sediment losses from roads where the losses drop with time after construction.

Regression analyses were conducted to obtain a predictive equation for plume length on old roads as a function of the measured variables. Using stepwise regression, six equations were derived that describe the relation of plume length to measured road variables. Two of these equations are shown here. Equation 1 was chosen where the $r^2$ value seemed to level off with the addition of more variables.

$$\text{plume length (m)} = 1.819 + 1.132*X162 + 0.042*X151 - 0.02843*X77 \qquad (1)$$

$$r^2 = 0.523 \qquad \text{std error} = 3.1 \text{ m}$$

where :

X162 = distance to initial obstruction (m)

X151 = hillside slope (%)

X77 = cutslope cover(%)

or:

$$\text{plume length (m)} = -0.546 + 1.126*X162 + 0.0422*X151 - 0.0335*X77\ 1.09*X80 + 0.0124*X10 - 1.264*X7 \qquad (2)$$

$$r^2 = 0.578 \qquad \text{std error} = 2.92 \text{ m.}$$

where :

X80 = road aspect (0=north, 1=south,2=east/west)

$X10$ = road length (m)

$X7$ = soil group (0=coarse, 1=fine)

In Equation 2, road length between culverts is only one of six variables that could be used in evaluating the sediment performance in old roads. When adding three variables to the first equation, the $r^2$ improves from 0.523 to 0.578 and the standard error improves only by 0.2 m. This is not enough of an improvement to warrant using the extra variables unless road length is specifically desired to be included in the equation.

For newly constructed roads, four equations were obtained from the stepwise regression analysis. None of these included road length although road length and plume length were significantly correlated (Table 7). Since the road length is highly correlated with cutslope area the equation indirectly includes the road length. The best equation found was :

$$\text{plume length (m)} = 12.337 + 1.391*X142 + 3.181*X141 - 27.538*X26 + 0.0045*X75 \qquad (3)$$

$$r^2 = 0.841 \qquad \text{std error} = 4.54 \text{ m}$$

where :

$X142$ = fillslope length (m)

$X141$ = fillslope contributing width (m)

$X26$ = ditch depth (m)

$X75$ = cutslope area ($m^2$)

In addition to this regression equation, a simple regression was used to derive and equation relating plume length to road length. This equation was:

$$\text{plume length (m)} = -8.773 + 0.123*X10 \qquad (4)$$

$$r^2 = 0.349 \qquad \text{std error} = 9.18 \text{ m}$$

where :

$X10$ = plume length (m)

The single equation has double the standard error and explains 49 percent less of the variance in the plume length than the four variable equation.

**Discussion**

For newly constructed roads, Table 7 shows the correlation between significant field variables and plume length. Of the seven variables, road length and fillslope properties (width and length) are the most significant.. On older, more established roads (Table 6), the distance to obstructions and the USLE LS factor showed positive and significant correlation with sediment plume lengths.

For established roads, hillside slope is significantly and positively correlated with increased sediment travel distances. This is likely related to the overland flow needed for sediment transport; as hillsides steepen, sediment can be transported further downhill.

Equation 1 also includes a variable for cutslope cover on established roads. This vegetation variable is significantly and negatively correlated with increased sediment travel distances; as vegetation is established and the cover increased, sediment travel distances are shortened. Added root strength and protective soil cover from raindrop splash erosion are likely reasons transport distances are reduced as vegetation becomes established along the road prism.

Plume lengths are affected by an initial distance to an obstruction placed below the culvert. The placement of debris at the culvert outfall could detain and/or dissipate runoff, allowing sediment to settle out and deposit nearby, shortening the sediment plume length. Mean distance from the culvert opening to the initial obstruction, as well as mean travel distances by type are shown in Table 8.

Placement of obstructions within the first one or two meters immediately after a culvert opening may reduce the plume length to less than 10 meters. For the new road slash, two of the seven plume lengths were very large, resulting in a very high mean length. Comparisons of obstruction trap efficiency, placement, and cost effectiveness was not a part of this study but certainly could

be included in future studies.

For newer roads, road length is a significant parameter, and positively correlated with sediment travel distances. As road length between culverts increases, the longer contributing section results in more opportunity to generate runoff and sediment which will contribute to longer sediment plumes below the culvert outfall. Mean plume lengths are compared to road lengths between culverts in Table 9. This table shows that plume length increases significantly once culvert spacing is over 200 m. Thus every effort should be made not to exceed this spacing.

## CONCLUSIONS

Excess sediment from logging roads is both a road maintenance and ecological problem. Initial sediment delivery distances below the roads from designed surface drainage features can be predicted and minimized by knowing optimal lengths and slopes between culverts.

Analysis of site-specific parameters in the Oregon Coast Range have shown that fillslope contributing length and width, ditch depth and cutslope area (road length*cutslope width) are important design variables for new roads when one wishes to minimize plume lengths below cross-drains. Once roads have been built, it is often too late to alter design criteria such as road slope and culvert spacings. Obstructions below the culvert openings, such as woody debris from logging slash, placed rock, or settling ponds tend to reduce the length of the sediment plume produced along the road prism for older roads. In the initial stages of road design and prior to building logging roads, distances between culverts and placement of debris should be considered as the primary method to reduce initial sediment delivery distances from roads toward receiving streams. Road slope can sometimes also be altered to further reduce sediment travel distance, though not quite as easily when dictated by natural topography and geology.

The empirical prediction models developed here were appropriate for measured variables as observed during the summers of 1995 and 1996. These equations best predict sediment travel distance from the variables provided. These models are appropriate for roads constructed under similar conditions, with similar soil types and hydrologic regimes.

These results further validate the importance of established vegetation, riprap, or debris placement at the toe of fillslopes below culverts to reduce long-term downhill sediment transport distances.

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Table 1. Observed sediment travel distances below culverts

| Road age | N | Mean (m) | Std. Dev (m) | min (m) | max (m) |
|---|---|---|---|---|---|
| Old | 96 | 5.09 | 4.48 | 0.1 | 23.2 |
| New | 24 | 9.33 | 11.37 | 1.34 | 40.5 |
| Total | 120 | 5.94 | 6.63 | 0.1 | 40.5 |

Table 2 Observed sediment plume length by downhill slope

| Age | downhill slope (low < 9%) | N | Mean (m) | Std. Dev (m) | min (m) | max (m) |
|---|---|---|---|---|---|---|
| Old | low | 48 | 5.78 | 5.18 | 23.2 | 0.1 |
| | high | 48 | 4.40 | 3.56 | 15.6 | 0.1 |
| | total | 96 | 5.09 | 4.48 | 23.2 | 0.1 |
| New | low | 13 | 5.15 | 3.67 | 12.98 | 1.34 |
| | high | 11 | 14.27 | 15.23 | 40.5 | 3.57 |
| | total | 24 | 9.33 | 11.37 | 40.5 | 1.34 |
| All | low | 61 | 5.65 | 4.88 | 23.2 | 0.1 |
| | high | 59 | 6.24 | 8.08 | 40.5 | 0.1 |
| | total | 120 | 5.94 | 6.63 | 40.5 | 0.1 |

Table 3 Observed sediment plume length by road LS factor

| Age | LS Factor | N | Mean (m) | Std. Dev (m) | min (m) | max (m) |
|---|---|---|---|---|---|---|
| Old | low | 41 | 3.41 | 2.77 | 0.1 | 11.2 |
| | high | 55 | 6.34 | 5.08 | 0.1 | 23.2 |
| | total | 96 | 5.09 | 4.48 | 0.1 | 23.2 |
| New | low | 6 | 4.05 | 3.57 | 1.34 | 11.03 |
| | high | 18 | 11.09 | 12.58 | 2.77 | 40.5 |
| | total | 24 | 9.33 | 11.37 | 1.34 | 40.5 |
| All | low | 47 | 3.49 | 2.84 | 0.10 | 11.20 |
| | high | 73 | 7.51 | 7.81 | 0.1 | 40.5 |
| | total | 120 | 5.94 | 6.63 | 6.34 | 5.08 |

Table 4 Observed sediment plume length by soil texture

| Age | oil textur | N | Mean (m) | Std. Dev (m) | min (m) | max (m) |
|---|---|---|---|---|---|---|
| Old | coarse | 39 | 6.02 | 5.03 | 0.5 | 23.2 |
| | fine | 57 | 4.45 | 3.97 | 0.1 | 18.6 |
| | total | 96 | 5.09 | 4.48 | 0.1 | 23.2 |
| New | coarse | 16 | 11.44 | 13.42 | 1.34 | 40.5 |
| | fine | 8 | 5.10 | 2.87 | 2.77 | 11.03 |
| | total | 24 | 9.33 | 11.37 | 1.34 | 40.5 |
| All | coarse | 55 | 7.60 | 8.61 | 0.5 | 40.5 |
| | fine | 65 | 4.53 | 3.84 | 0.1 | 18.6 |
| | total | 120 | 5.94 | 6.63 | 0.1 | 40.5 |

Table 5 Observed sediment plume length by hillslope aspect

| Age | aspect | N | Mean (m) | Std. Dev (m) | min (m) | max (m) |
|---|---|---|---|---|---|---|
| Old | north | 23 | 5.80 | 5.41 | 1.2 | 23.2 |
| | south | 29 | 5.18 | 4.21 | 0.1 | 17.4 |
| | east/west | 44 | 4.66 | 4.16 | 0.1 | 16.9 |
| | Total | 96 | 5.09 | 4.48 | 0.1 | 23.2 |
| New | south | 9 | 12.06 | 14.28 | 1.49 | 40.5 |
| | east/west | 15 | 7.69 | 9.39 | 1.34 | 39.5 |
| | Total | 24 | 9.33 | 11.37 | 1.34 | 40.5 |
| All | north | 23 | 5.80 | 5.41 | 1.2 | 23.2 |
| | south | 38 | 6.81 | 8.14 | 0.1 | 40.5 |
| | east/west | 59 | 5.43 | 5.99 | 0.1 | 39.5 |
| | Total | 120 | 5.94 | 6.63 | 0.1 | 40.5 |

Note: There were no new roads with north hillslope aspect

Table 6 Old road plume lengths correlations with field variables

| Variable | Correlation significance (2-tailed) |
|---|---|
| Road slope (%) | 0.01 |
| Ditch depth (m) | 0.005 |
| USLE LS factor (high or low) | 0.001 |
| Cutslope cover (%) | 0.048 |
| Hillside slope (%) | 0.009 |
| Hillside cover (%) | 0.025 |
| Distance to initial obstruction (m) | 0 |

Table 7 New road plume lengths correlations with field variables

| Variable | Correlation significance (2-tailed) |
|---|---|
| Road length (m) | 0.001 |
| Curtlope area (sq. m) | 0.006 |
| Hillside slope (%) | 0.034 |
| Hillside slope (high or low) | 0.048 |
| Fillslope width (m) | 0 |
| Fillslope length (m) | 0 |
| Obstruction type ( categorical) | 0.041 |

**Table 8** Mean distance to initial obstructions and mean plume length for each type of obstruction.

| Type of Obstruction | Old Roads | | | New Roads | | |
|---|---|---|---|---|---|---|
| | N | Mean distance to obstruction (m) | Mean plume length (m) | N | Mean distance to obstruction (m) | Mean plume length (m) |
| Slash, logging debris, windrow | 16 | 2.16 | 5.85 | 7 | 3.23 | 16.32 |
| Downed woody debris (logs, branches) | 28 | 2.42 | 6.21 | 11 | 1.34 | 8.20 |
| soil berm | 22 | 1.63 | 3.73 | 5 | 0.14 | 3.32 |
| rock, riprap | 11 | 2.56 | 5.36 | 11 | 0.98 | 2.90 |

**Table 9.** Mean plume length compared to contributing lengths between culvert installations on new roads.

| Distance Between Culverts (m) | Number of roads | Mean plume length (m) |
|---|---|---|
| < 50 | 1 | 1.34 |
| 50-100 | 4 | 2.82 |
| 100-150 | 5 | 4.48 |
| 150-200 | 10 | 6.28 |
| 200-250 | 4 | 31.52 |